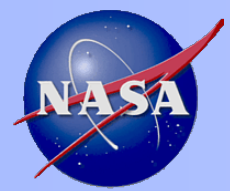


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Second Harmonic Passive Thermography Generated by Cyclic Loading in Composites

William P. Winfree, Joseph N. Zalameda, and Elizabeth Gregory
NASA Langley Research Center Hampton, VA 23681

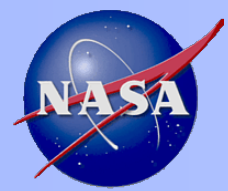
Thermosense: Thermal Infrared Applications XL
Orlando, FL
April 15-19, 2018



Outline

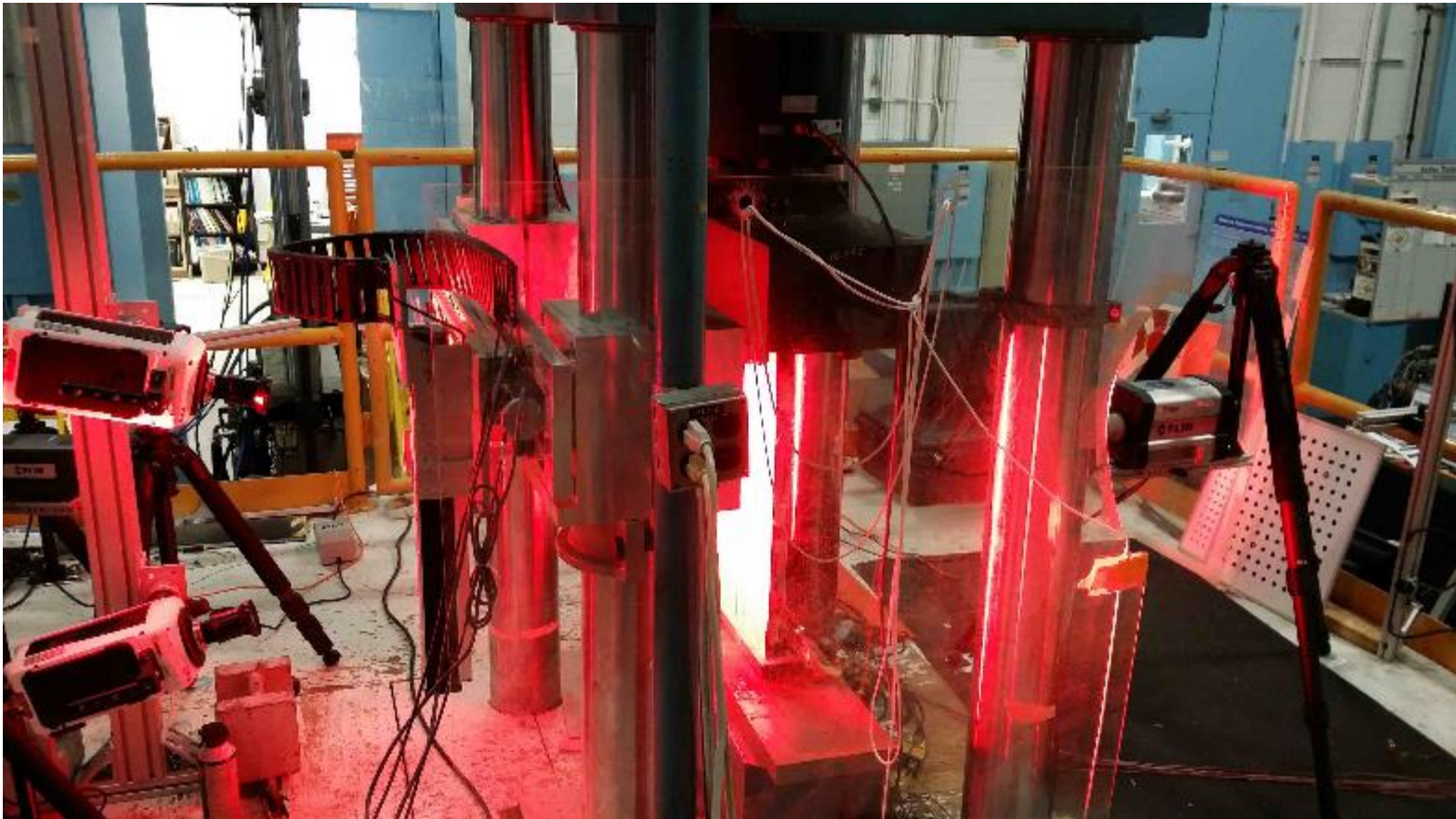
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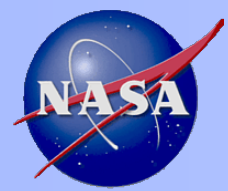
- Introduction
- Passive Thermography for In Situ Inspection
 - Identification of points with large harmonic content in thermal responses
- Modeling
 - Phase from Friction Heating
 - One Dimensional Series Solution
 - Two Dimensional Quadrupole Solution
- Comparison Model Output and Measurements
- Summary



Load Testing Configuration

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Passive Thermography

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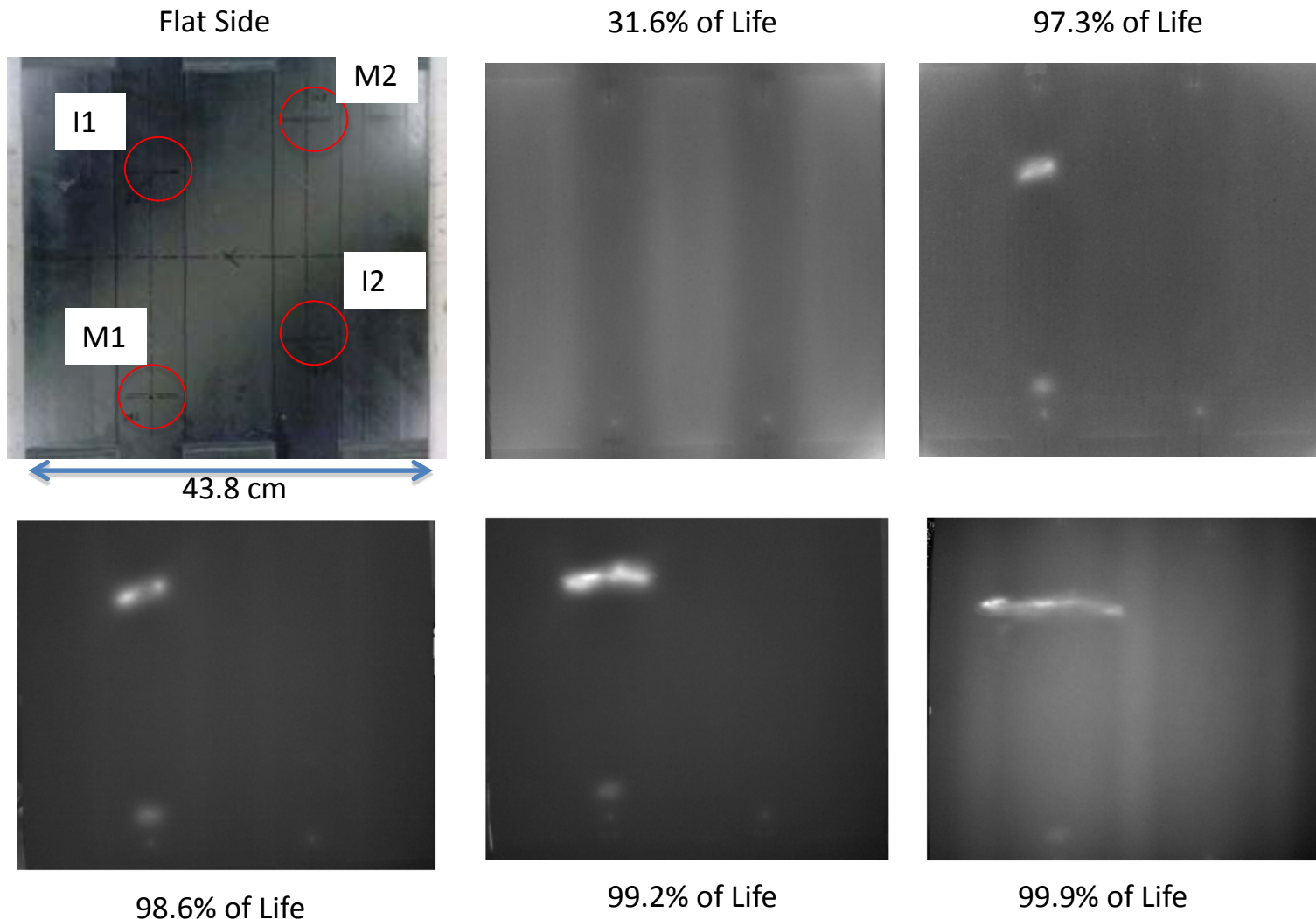


- Passive thermography provides wide area inspection of a composite structure during load testing to monitor damage growth and determine when to stop the fatigue loading.
- Most prior efforts have focused on responses that occurs at the same frequency as the cyclic loading
- At some points there is a significant signal at twice the frequency – the phase of these points fall in a relatively small range



Real Time Inspection Passive Thermography Raw Images

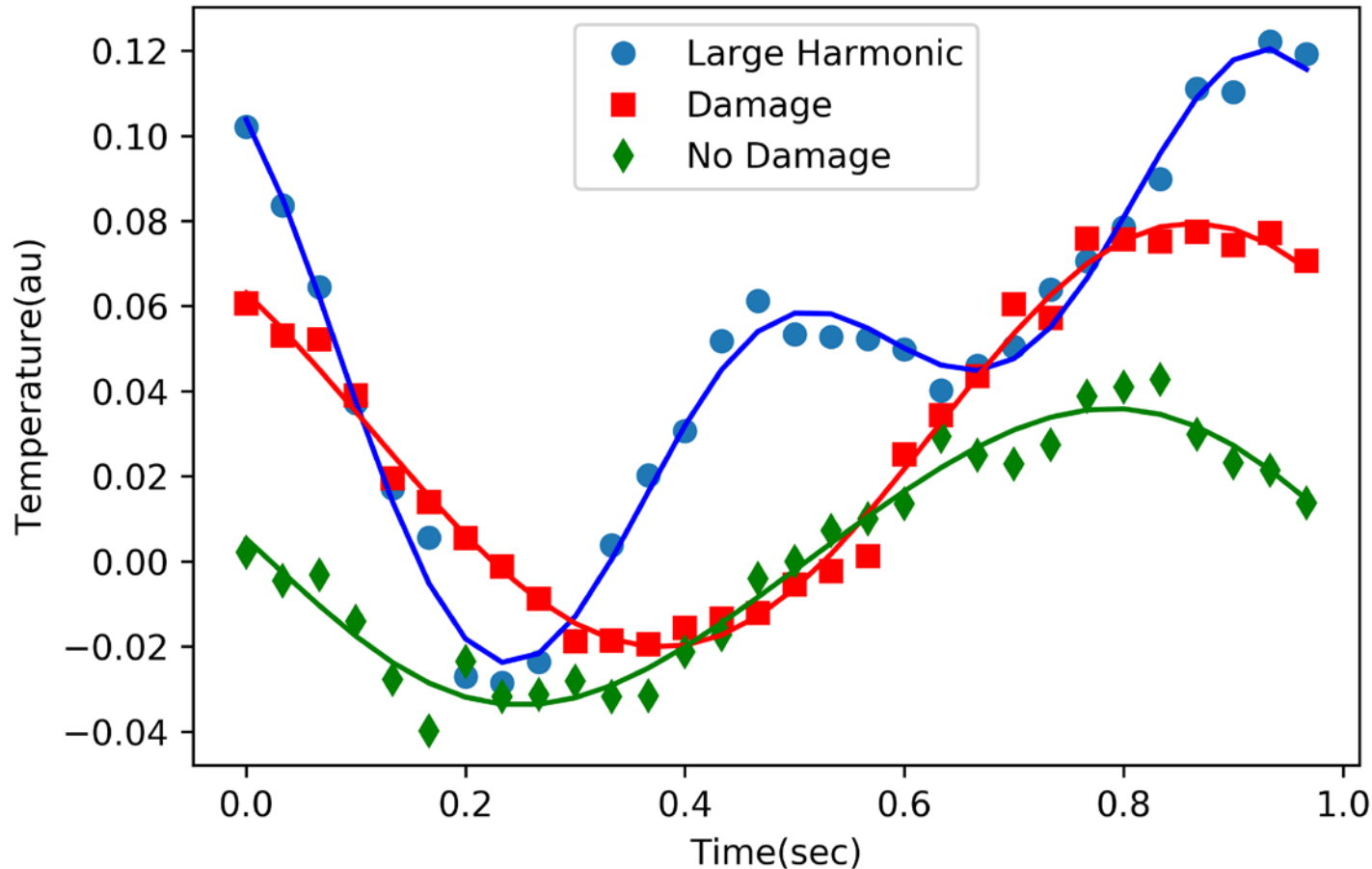
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Thermal Responses from Flawed, Unflawed Regions and Points with Large Harmonics

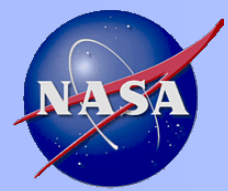
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Solid Lines are fits of responses with:

$$T(t) = a_0 + a_1 t + a_2 \cos(\omega t) + a_3 \sin(\omega t) + a_4 \cos(2 \omega t) + a_5 \sin(2 \omega t)$$

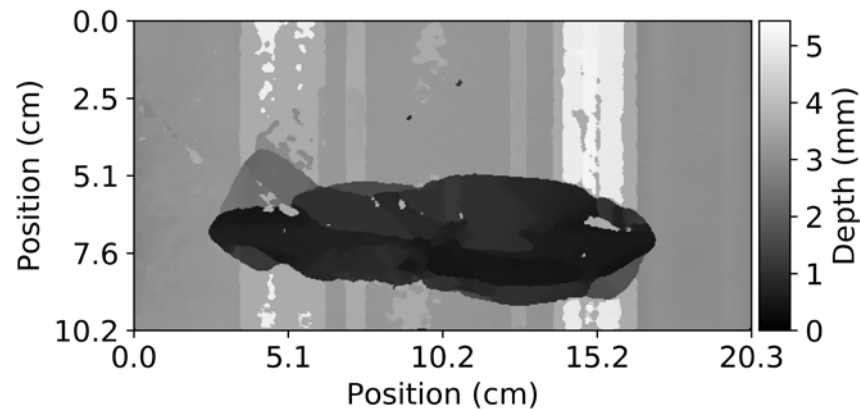
$$\omega = 4 \pi / \text{sec}$$



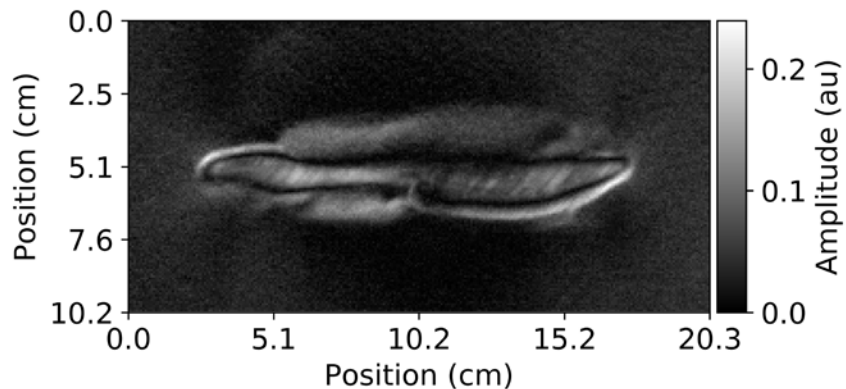
UT Depth Map and Passive Thermography Maps

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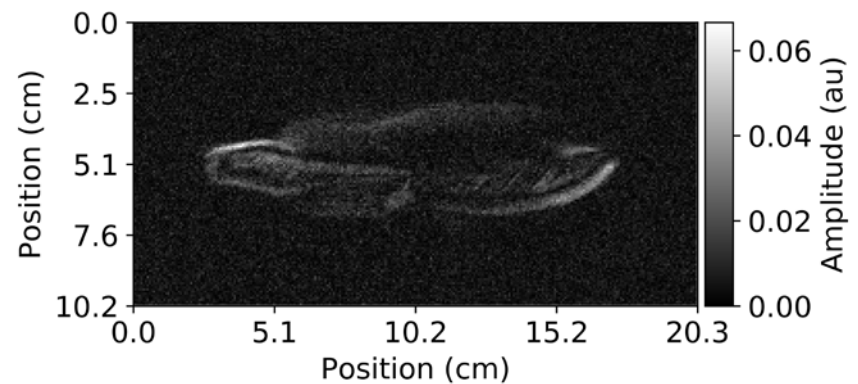
Depth of Damage from UT Measurement

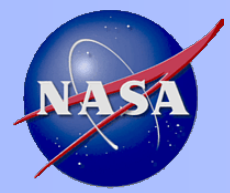


Amplitude of Passive Thermography
Fundamental



Amplitude of Passive Thermography
Harmonic



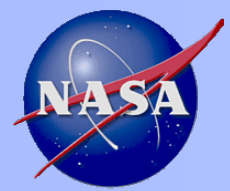


Points with Largest Passive

Thermography Harmonic Amplitudes

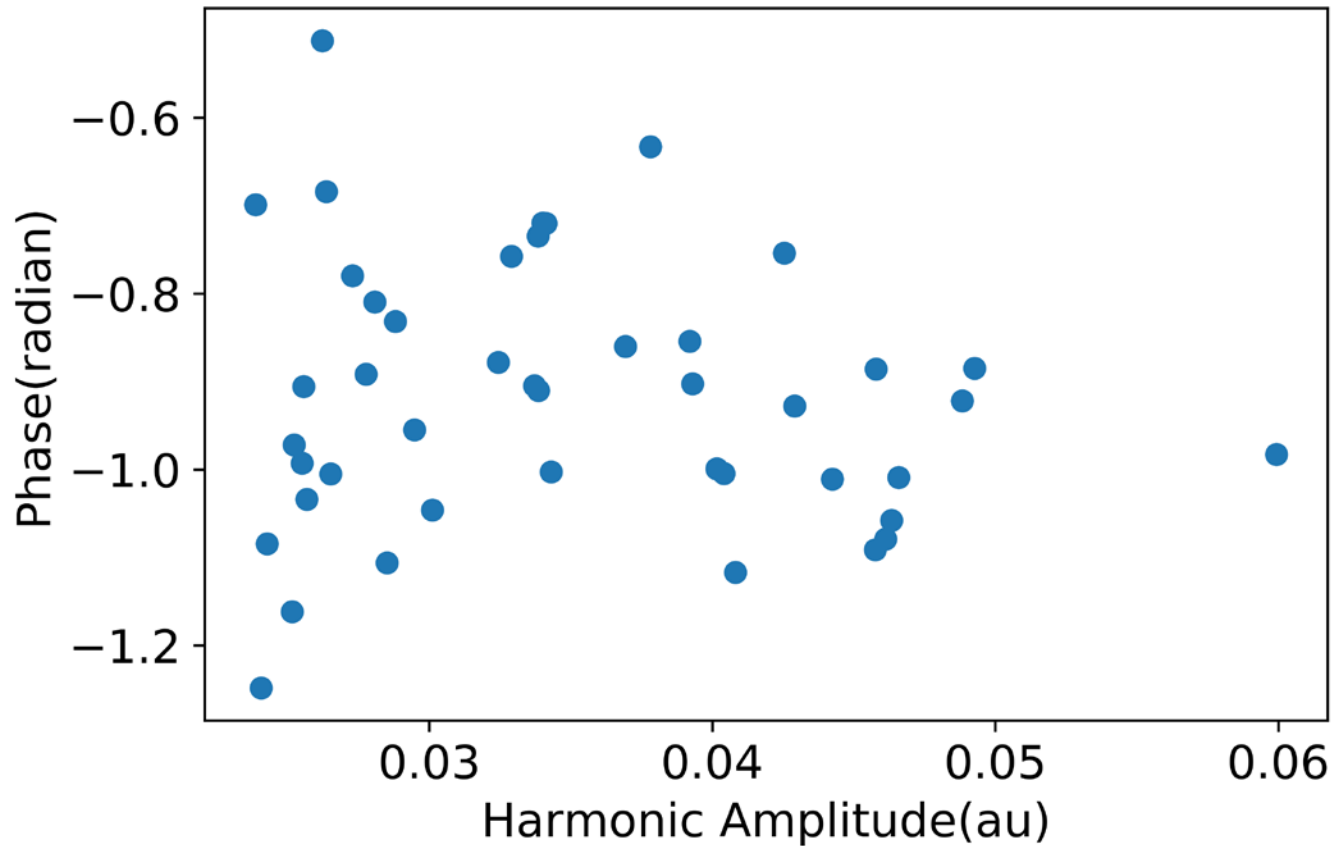
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Phases for Large Amplitude Harmonic Responses

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Average phase = -0.90 rad

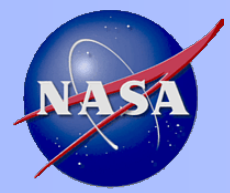
Standard Deviation = 0.15 rad



Simple Friction Source

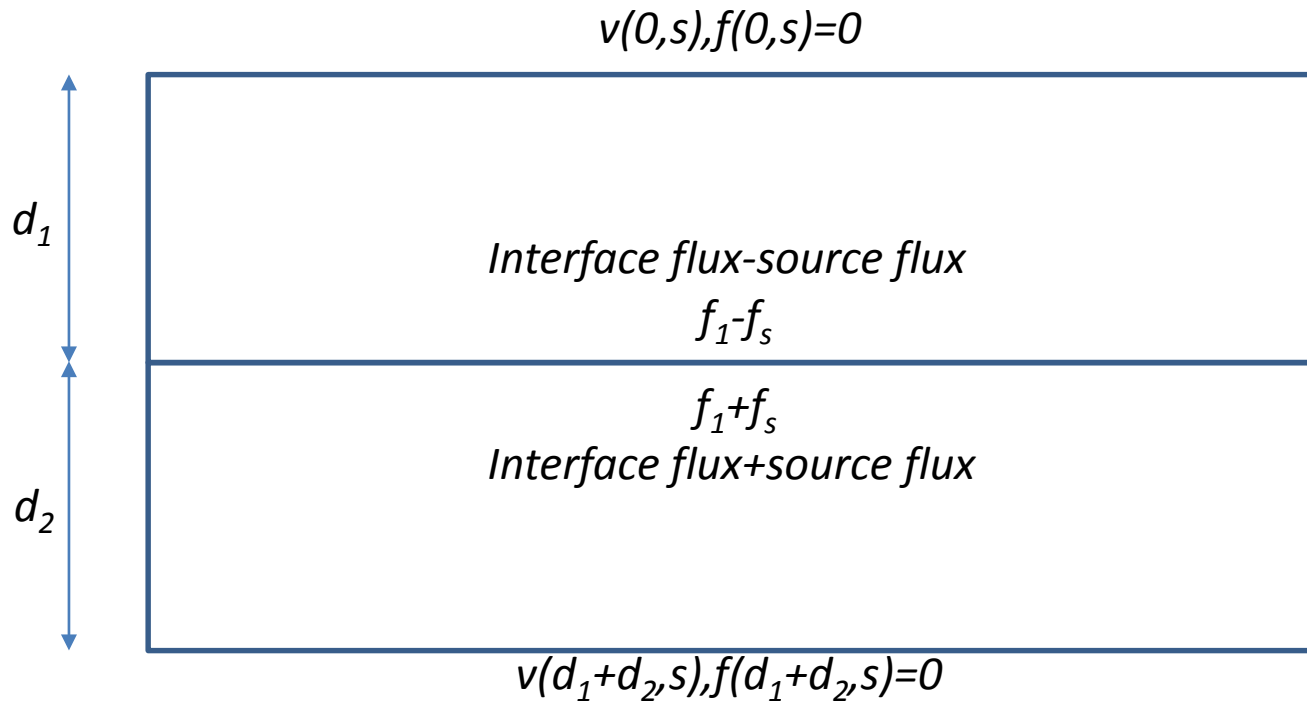
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- Focus is determining the phase
- Power expended in moving object against force –
 $P = \overline{F} \bullet \overline{v}$ where v is the velocity
- v is relative movement of two surfaces of a delamination
- Assume amplitude of \overline{F} is constant
- Relative displacement of surfaces is proportional to $\sin(\omega t)$
- Magnitude of velocity proportional to $|\cos(\omega t)|$
- Power proportional to $|\cos(\omega t)|$



One-Dimensional Model with Subsurface Source

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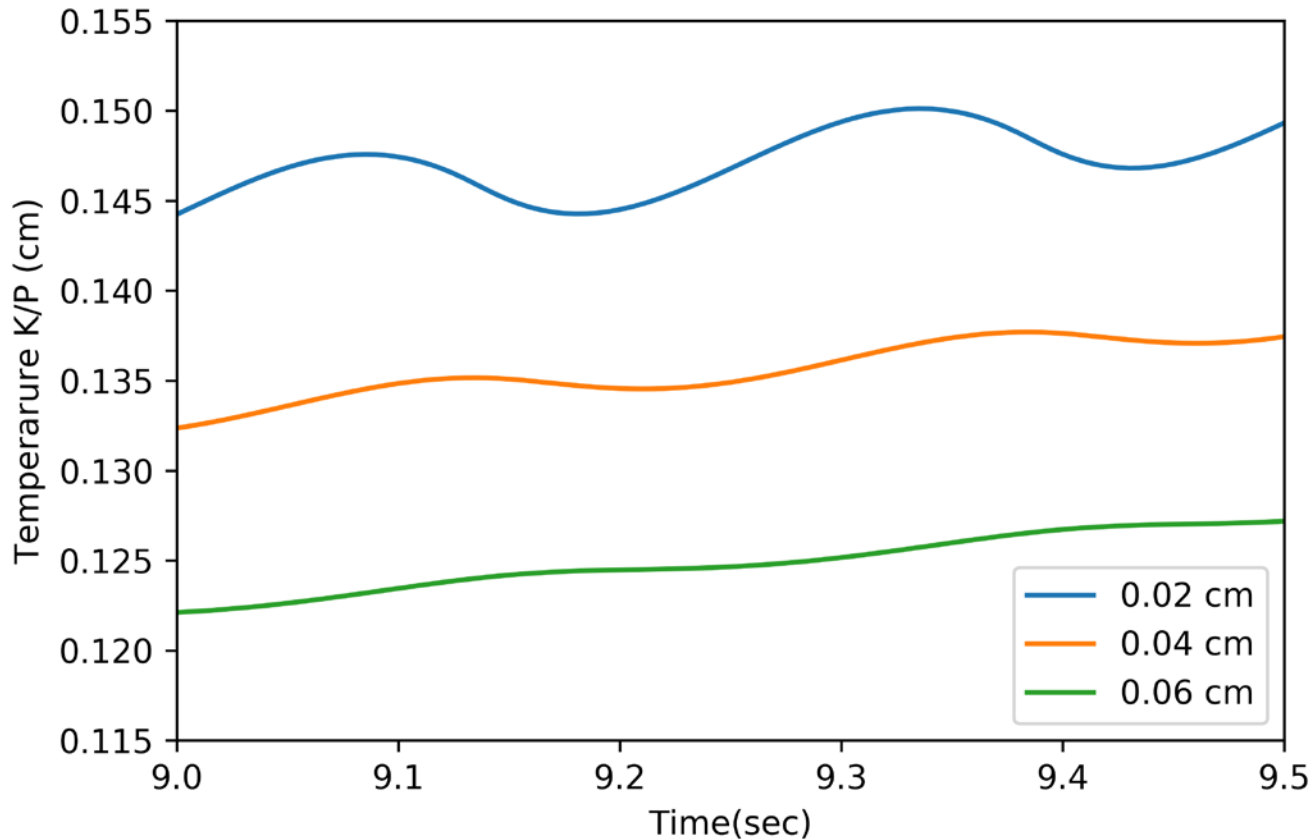


- Interface flux is the result of a temperature gradient at the interface and needs to be solved for
- Source flux, f_s , is from heat generated at the interface, $f_s = C |\cos(\omega t)|$
- Series solution is possible (details in paper)

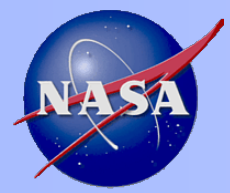


Series Solution for $P |\cos(\omega t)|$ Source at Different Depths Below Surface

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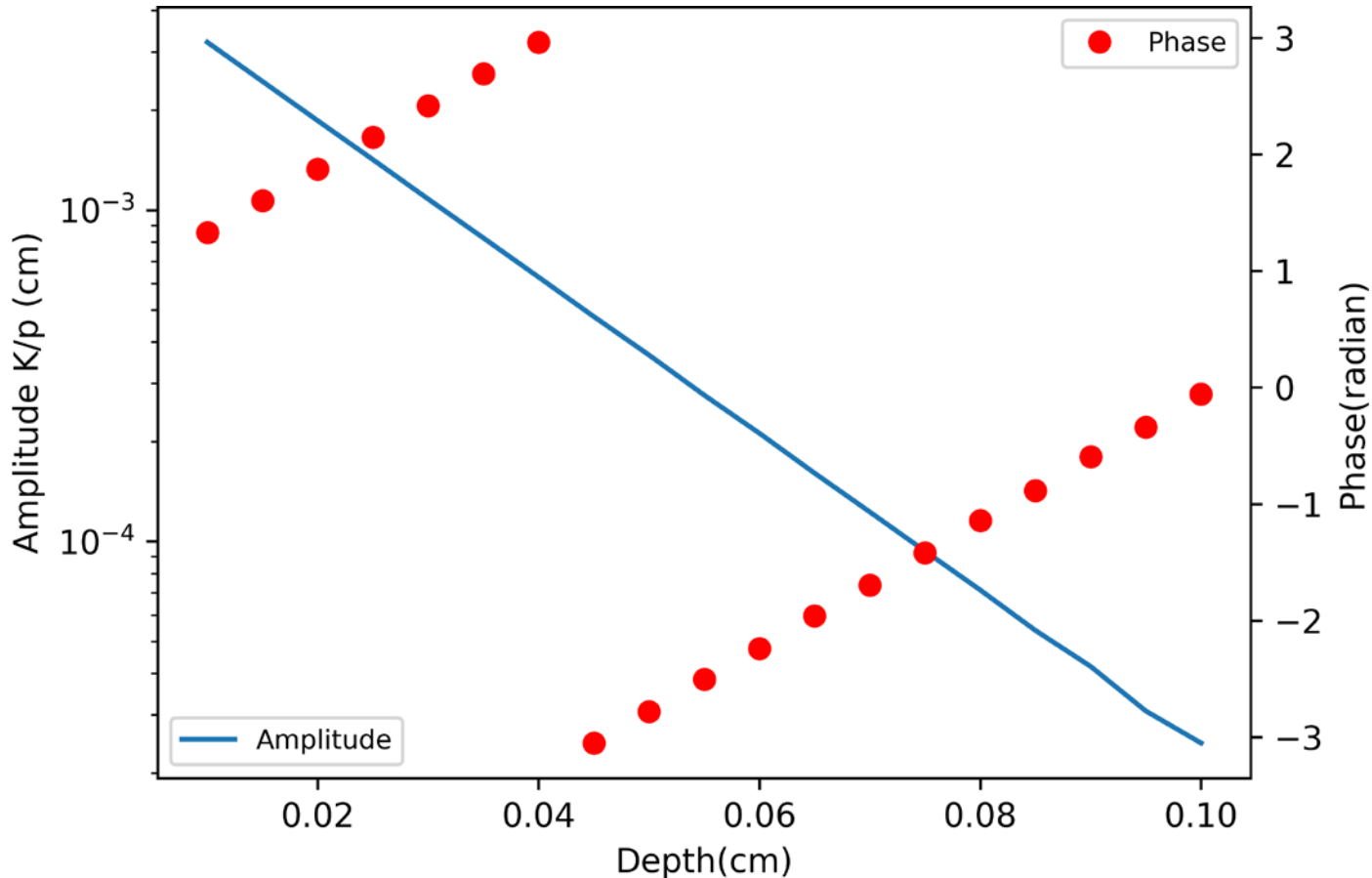


Block thickness is 0.32 cm,
Diffusivity=0.00425 cm²/sec, Frequency=2 Hz



Amplitude and Phase for Different Depth Sources

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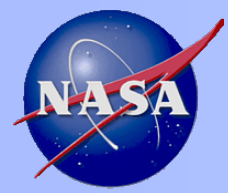


Source $p |\cos(\omega t)|$ at different depths in 0.32 cm thick block,
Diffusivity = $0.0045 \text{ cm}^2/\text{sec}$

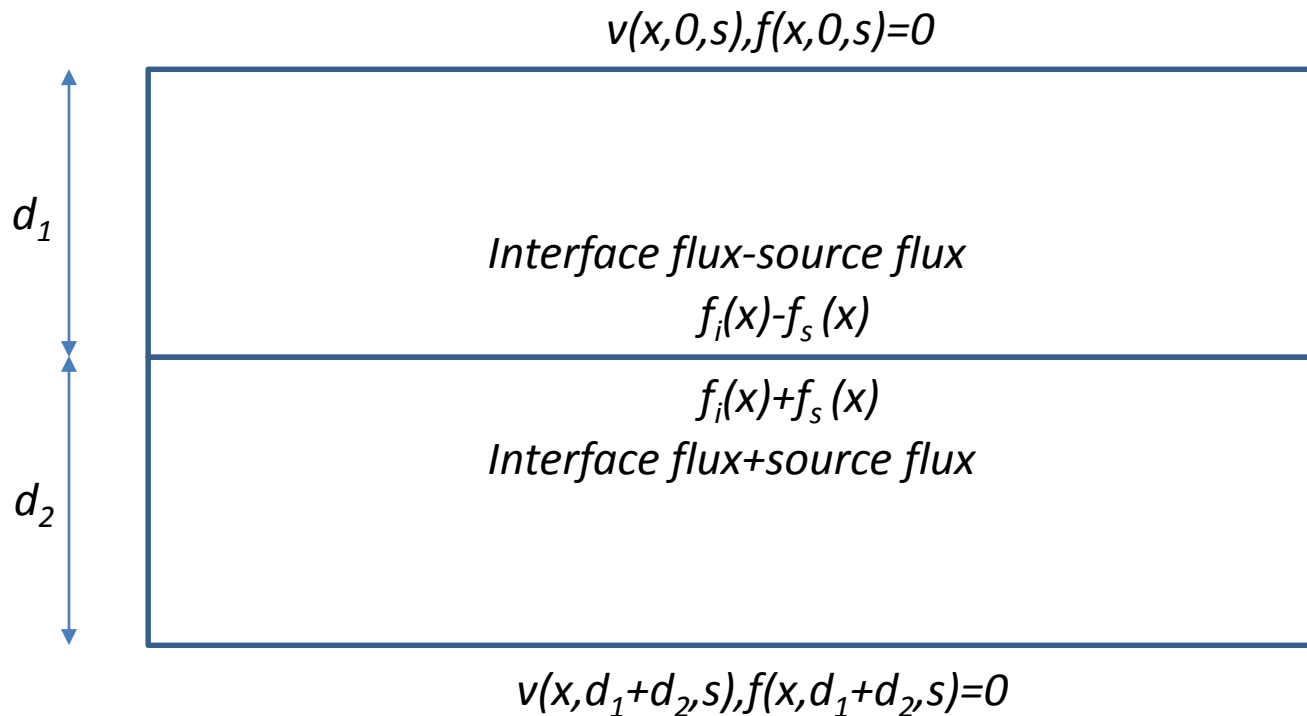
Phase is approximately linearly dependent on source depth

Estimate of depth of harmonic source based on phase – $0.084 \pm 0.003 \text{ cm}$

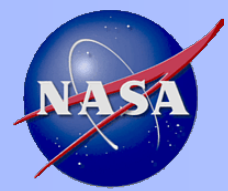
Delamination depth based on UT measurement – 0.06 cm



Two-Dimensional Model with Subsurface Source

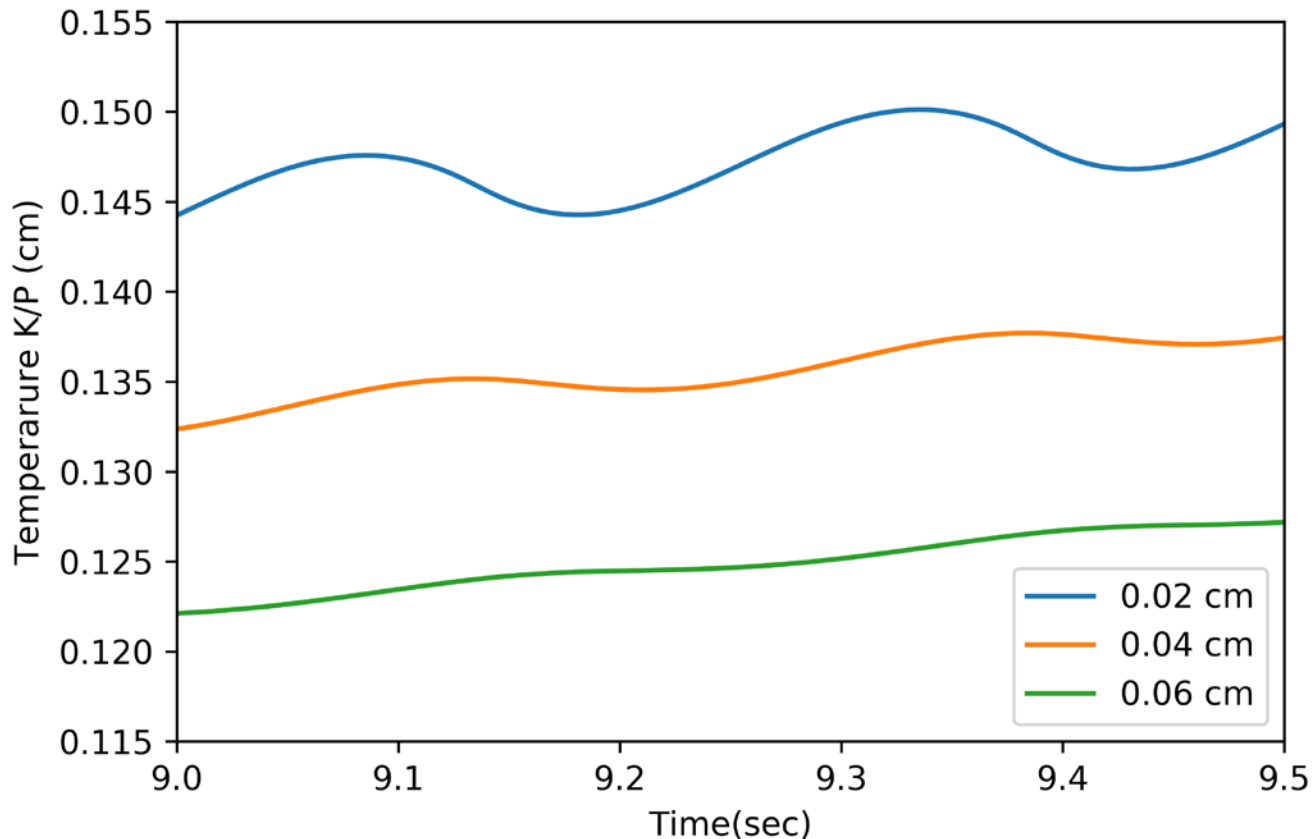


- $v(x,0,s)$ found for using quadrupole method (details in paper)
- Source flux $f_s(x)$, is spatial variation in the heat source at the interface
- Assume $f_i(x)=P|\cos(\omega t)|\delta(x-x_0)$ – Point source 2D (Line Source 3D)



Line Source Response for $P |\cos(\omega t)|$ Source at Different Depths Below Surface

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Block thickness is 0.32 cm,

Diffusivity=0.0045 cm²/sec, Frequency=2 Hz

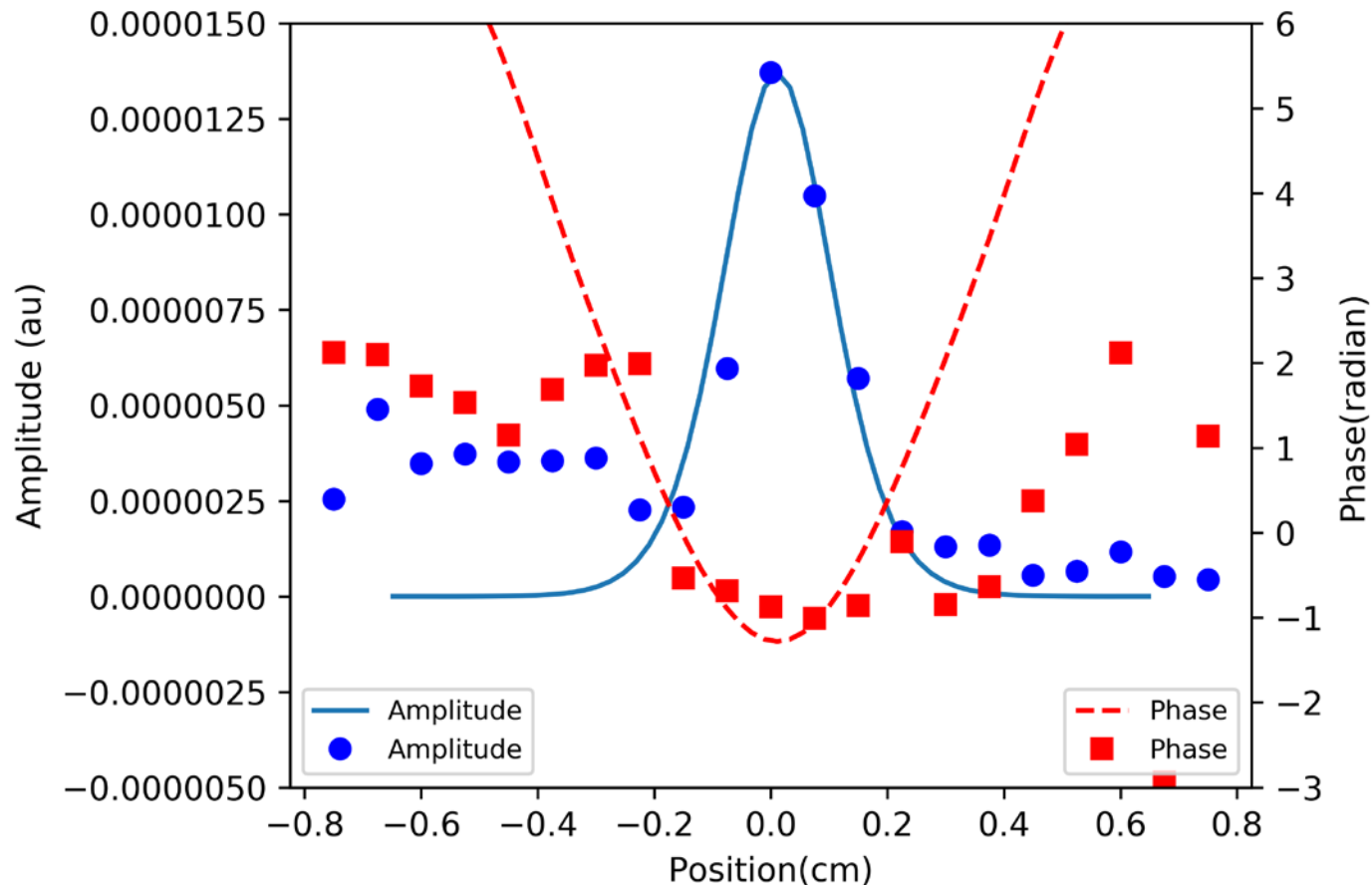
Amplitudes significantly less than for planar source (1D solution)

Phase is approximately the same

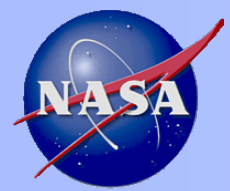


Comparison of Experimental and Simulation Responses

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Simulation Parameters - Block thickness is 0.32 cm, Source Depth-0.085 cm
Surface Normal Diffusivity=0.0045 cm²/sec, In-plane Diffusivity 0.025 cm²/sec
Frequency=2 Hz



Summary

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- Passive thermography has a significant harmonic at distinct locations near edges of subsurface delamination.
- Phases of all significant harmonic responses are approximately the same.
- From one-dimensional series solution assuming a simple friction source, an estimation of a source depth is 0.084 cm, which is in reasonable agreement with ultrasonic measurements (0.06 cm).
- A two-dimensional simulation is in reasonably good agreement with spatial variation of both the phase and amplitude of the measured response